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Multiple Interactions, Intermittency, and Other Studies*

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Abstract:
An overview is given of some Lund-based models for multiparticle production in e^+e^- annihiliation, leptoproduction and hadron interactions. Special emphasis is put on a model for multiple parton-parton interactions in the latter process. Results are presented for some new studies on intermittency, with particular reference to jet production and Bose-Einstein effects.

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1. Introduction

Today, several different "Lund models" exist for multiparticle production in various processes. They are all based on the same Lund string fragmentation scheme,[1)] in which quarks, antiquarks and diquarks are viewed as endpoints of the fragmenting strings, and gluons as energy and momentum carrying kinks. This scheme is implemented in the Monte Carlo program JETSET,[2)] and seems to provide a better description of the data than any other model available today.[3)]

In order to give a complete description of the event structure in different reactions, it is also necessary to specify how the fragmenting system of partons is produced, and how those partons are connected in colour space. Given a hard interaction, one approach is here based on a parton shower picture of subsequent $q \to qg$, $g \to gg$ and $g \to q\bar{q}$ branchings,[4)] another on dipole branchings.[5)] Conceptually, the two descriptions are dual to one another. For e^+e^- annihilation, the choice seems to be mainly one of convenience: the two approaches tend to give similar results if the same kinematical constraints are imposed. In leptoproduction, the dipole approach offers a conceptual advantage, in that the separate initial and final state shower algorithms can be replaced by one single dipole description, but this is to be balanced against an uncertainty in how large the initial radiating dipole is. Visible differences between the two schemes are here predicted at HERA energies.[5)]

It is for hadron-hadron interactions, however, that a full-scale (but friendly) "civil war" is in progress between two main models originating from members of the Lund group: the PYTHIA one[6,7)] and the FRITIOF one.[8)] The latter has as main assumption that no net colour exchange takes place between the two interacting hadrons, but that interactions only excite the hadrons into higher-mass string states, with kinks given by the hard interaction and subsequent dipole radiation. In PYTHIA, on the other hand, hard interactions are associated with colour exchange between the hadrons, according to the rules of perturbative QCD (with the neglect of some interference terms that are vanishing in the limit of infinitely many colours). Further, it is assumed that several parton pairs from the two incoming hadrons may interact, more or less independently of each other, such that complicated multistring configurations may arise. This latter possibility is the subject of sections 2 and 3. Initial and final state radiation in PYTHIA is handled within the parton shower approach.

For high-p_T events, a study has been presented,[9)] in which PYTHIA, FRITIOF and other Monte Carlos are compared, both with respect to conceptual foundations and to experimental predictions. In particular, the absence of configurations with more than two fragmenting strings in FRITIOF is compensated by a more prolific (dipole) parton radiation, which leads to quite a different jet structure. Data from the $Sp\bar{p}S$ and TeV I colliders could therefore be used to distinguish between several aspects of the models.

One of the most widely discussed subjects of this workshop was intermittency,[10)] and the extent to which this could be caused by parton cascading. Some simple Monte Carlo studies on this subject are presented in section 4.

2. The Multiple Interactions Model

The differential cross-section for a hard parton-parton interaction is given by perturbative QCD, as a convolution of the hard scattering matrix elements and the structure functions of the incoming hadrons. The integrated cross-section of all interactions with transverse momentum $p_T > p_{Tmin}$, $\sigma_{hard}(p_{Tmin})$, is divergent for $p_{Tmin} \to 0$. At present Collider energies, $\sigma_{hard}(p_{Tmin})$ becomes comparable with the total cross-section for $p_{Tmin} \approx 1.5$ - 2.0 GeV. This need not lead to contradictions: $\sigma_{hard}(p_{Tmin})$ does not give the hadron-hadron cross-section but the parton-parton one. Each of the two incoming hadrons may be viewed as a beam of partons, with the possibility of several parton-parton interactions when the hadrons pass through each other, so that $\sigma_{hard} > \sigma_{tot}$ is perfectly allowed.

A comparison with Collider data indicates a significant probability for multiple interactions at 540 GeV.[7)] Specifically, if at most one hard interaction is allowed per event in the PYTHIA program, the predicted multiplicity distribution is much narrower than the UA5 one, and the experimentally observed forward-backward multiplicity correlations are almost absent.

If, for any given hadron-hadron collision, several different parton interactions above p_{Tmin} are assumed to take place (essentially) independently of each other, one obtains a Poissonian multiplicity distribution in the number of interactions, with mean given by $\sigma_{hard}(p_{Tmin})/\sigma_{tot}$, where σ_{tot} is the total inelastic, nondiffractive cross-section. With a varying number of interactions in an event, the multiplicity fluctuations are increased, and strong forward-backward multiplicity correlations are introduced. Results are sensitive to the choice of p_{Tmin} value, with a reasonable description of the multiplicity distribution obtained for $p_{Tmin} \approx 1.6$ GeV. The presence of some regularization of the divergent parton-parton cross-section can be motivated by the fact that the incoming hadrons are colour singlets: a gluon of small p_T, and hence large transverse wavelength, will not resolve the individual colour charges inside the hadrons and therefore effectively decouple.

Up to this point, it has been assumed that the initial state of all hadron collisions is the same, whereas in fact each collision is also characterized by a varying impact parameter *b* (here *b* is to be thought of as a distance of closest approach, not as the Fourier transform of the momentum transfer). A small *b* value corresponds to a large overlap between the two colliding hadrons, and hence an enhanced probability for multiple interactions. A large *b*, on the other hand, corresponds to a grazing collision, with a large probability that no parton interactions at all take place. This variation will tend to broaden the minimum bias multiplicity distribution at higher energies. At present energies the change in the multiplicity distribution is less dramatic, since the mean number of interactions is small anyhow. Note, however, that events containing hard interactions are biased towards small impact parameters, and hence have a larger than average multiple interaction probability.

Different matter distributions inside the colliding hadrons have been studied, with the maybe unexpected result that data seem to indicate the need for large fluctuations in matter density. The latter may be parametrized e.g. by a double Gaussian, where half the matter is concentrated in a region a fifth the radius of the other half. The physical picture may be that of a hard core, or several cores corresponding to the three valence quarks.

The most direct evidence for this picture comes from the observation of four-jet events with the expected multiple interaction kinematics in the AFS detector,[11] and at a rate consistent with the model above. The UA1 multiple minijet rate,[12] Table 1, can also be interpreted as a good signal, in that we can only understand the high rate of 3- and 4-jet events by invoking multiple interactions. On the other hand, the UA2 Collaboration has recently set a limit on the multiple interaction rate,[13] at a level which is almost in contradiction with our model.

In addition to giving a fair description of minijet data, the model also reproduces the UA1 jet profile and, in particular, the energy flow away from the jet core (the "pedestal" effect),[14] Fig. 1. Up to roughly 10 GeV jet energy the underlying event activity increases, because events become more and more biased towards small impact parameter. Above that energy, with events already maximally biased, the small drop in underlying event activity is mainly related to the transition from $gg \to gg$ to $q\bar{q} \to q\bar{q}$ interactions.

Further details of the model and comparisons with data may be found in Ref. 7.

3. Multiple Interactions in Perspective

One of the objectives of these proceedings is to put models in perspective, i.e. to discuss similarities and differences. Hence the following comments.

At the time I formulated the multiple interaction model, a sharp split existed between low-p_T and high-p_T models. This was most apparent in two-component models,[15] where the event structure was viewed as a superposition of a KNO-scaling low-p_T background and a non-scaling contribution from jets with $p_T > 5$ GeV. The DTU type models[16] only dealt with the production of longitudinal chains without transverse momentum; the one attempt[17] to introduce p_T was a purely phenomenological smearing recipe. Double hard parton scattering had been studied only for fairly large p_T values[18] (typically $p_T >$ 10 GeV), and was consequently viewed as something too rare to affect ordinary events.

My attempt was therefore to formulate a model where QCD-type interactions were solely responsible for parton production, from the highest p_T scales (jets) to the lowest ones (underlying events). An eikonalization of the QCD $2 \to 2$ cross-section, necessary to handle the large QCD cross-sections involved, then in a natural fashion leads to multiple interactions. It is still necessary to regularize the cross-section in the limit $p_T \to 0$ (to obtain a physically reasonable model and, for hadronic wave functions with infinite support, a mathematically consistent one). Comparisions with data lead to suggesting a typical cutoff scale $p_{T0} \approx 1.5 - 2$ GeV, and that multiple interactions play an important rôle for the event structure at Collider energies, both ideas new at that time.

Subsequently, two-component DTU models have been introduced,[19] where interactions either have $p_T > p_{Tmin} \approx 2$ GeV ("hard Pomeron") or $p_T = 0$ ("soft Pomeron"), with an empty gap in between. The continuous p_T spectrum of my model could be translated into a similar form if all interactions with $p_T < p_{Tmin}$ were reassigned to have exactly $p_T = 0$. The relation thus is a close one, even if the details obviously differ quite a lot. In the DTU model the Pomeron picture (which I do not make use of) leads to more precise predictions for the energy variation of interactions at low p_T and of total cross-sections than in my model, where the low-p_T regularization procedure to be used for the perturbative QCD cross-section is inherently uncertain. The DTU models also postulate a Gaussian matter distribution inside the colliding hadrons, while I claim no guiding physics principle here, and use data to infer larger fluctuations in local parton density than obtained with the Gaussian shape. In other respects, my model still is the more sophisticated one. One example is that gluons do not appear explicitly in current DTU models.

4. Intermittency

One of the main topics of this workshop turned out to be that of intermittency.[10,20] As "homework", the amount of intermittency present in the Lund model has been studied (cf. refs. 20,21). To this end, the rapidity range between -3.2 and +3.2 has been subdivided into 2^n bins, n = 0, 1, 2, .. , and correspondingly for the full azimuthal range. For the rapidity definition, the linear sphericity axis is used in e^+e^- annihilation and the beam axis in $p\bar{p}$ collisions, and all charged particles are assumed to have the pion mass. The definition of the factorial moments F_i of the charged multiplicity distribution in the bins is such that the expectation value $\langle F_i \rangle$ is independent of bin size if particle production is uncorrelated and uniform in the rapidity and/or azimuthal range considered, and increasing with decreasing bin size if particles are clustered on a scale smaller than the bin size considered. Moments have been normalized to unity, event by event, for the full phase space under study. Figures are only presented for the average second factorial moment $\langle F_2 \rangle$, in the case of a simultaneous subdivision of rapidity y and azimuth ϕ (such that bins are almost square, $\Delta y \times \Delta\phi = 6.4 \cdot 2^{-n} \times 2\pi \cdot 2^{-n}$).

In several scenarios, intermittency is viewed as a consequence of cascading, either on the partonic[22] or on the hadronic[23] level. In Fig. 2 the importance of gluon emission for e^+e^- results at the Z^0 peak is made amply clear: in the simple two-jet case the model even contains "anti-intermittency", i.e. a suppression of nearby particle production. A separate slicing in y and ϕ shows that the effect is really in the latter, i.e. is likely due to local p_T compensation. One may also note that a use of second order matrix elements, i.e. mainly of three-jet events, gives larger factorial moments than the more realistic multijet configurations obtained with parton showers. The reason for this is that showering leads to a broadening of the jet profile, and hence to a reduced probability for finding several particles nearby in rapidity or azimuth.

In the Lund model, the relation between cascading and intermittency is then not a statement about parton cascades as such, but rather that each parton in the end has to "cascade" (i.e. fragment) into hadrons. As a rule of thumb, production of jets with a typical tranverse momentum E_T leads to an

intermittent behaviour down to a bin size of roughly (1 GeV)/E_T, just from the ordinary width of jets. Which of the matrix element and parton shower approaches gives the largest factorial moments may depend on the process and the CM energy, but it is always true that with the total E_T shared between fewer partons the factorial moments display a rising trend down to smaller bin sizes, since jet cores then are narrower.

One particularly interesting issue is the extent to which Bose-Einstein (BE) effects might lead to intermittent behaviour. To study this, it is first necessary to have a model for BE effects. Such models have been proposed,[24,25] but are less than trivial to apply for multijet events. Instead an attempt was made to include a simple exponential parametrization for pions, corresponding to an effective source radius 1 fm = $(0.2\text{ GeV})^{-1}$ and effective strength 1 (i.e. a factor 2 enhancement at vanishing momentum separation). The naive approach to implement this parametrization would be to assign a weight to each pair of identical pions in an event, and then an event weight as the product of these pair weights. Unfortunately, such an algorithm turns out to be unstable: an event with a large multiplicity systematically receives a larger weight, so that the weighted average multiplicity is larger than the unweighted (normal) one. At smaller energies, the effect is not larger than that it could have been compensated by a slight retuning of the fragmentation parameters, but at larger energies the whole approach would break down. On physical grounds it is not unreasonable to expect a larger effective radius for high-multiplicity events, and some pairs could also be associated with weights below unity[25], so conceivably a more complex approach along these lines could still be made to work.

In this study, another way out is used, in which the basic event production takes place without any regard to BE effects, and only afterwards nearby identical particles are shifted towards smaller invariant masses by final state interactions. The amount of shifting introduced is chosen so as to reproduce the parametrized two-particle enhancement as a function of invariant mass. Since only pairwise shifts are considered, some overestimation of the input correlation is obtained from events with three or more nearby particles. By and large, it seems to be a reasonably well working method, but it may conceivably miss out on some aspects of a complete and correct description of BE effects.

In a slicing of y or ϕ separately, BE effects only increase $\langle F_2 \rangle$ by something like 0.01, but in the combined slicing by roughly 0.05. The increase is visible already at fairly large bin sizes, and is almost fully developed already at an edge size of 0.8. This may surprise, but should probably be understood as follows. Particles with large p_T sit inside jets, and go together or not depending on jet topology rather than on BE effects. Particles at low p_T, on the other hand, may be separated by a larger rapidity and still sit in the BE enhancement region. BE effects therefore seem to be of minor importance in understanding intermittency in e^+e^- events. (At 29 GeV, where the event weighting approach to BE effects can still be used sensibly, the increase in $<F_2>$ is almost twice as high in this approach as in the one used above, but this likely is only a result of weighting up events with higher-p_T jets and hence higher multiplicities.)

For 630 GeV $p\bar{p}$ PYTHIA minimum bias events, jet production is relatively less important, and the rise of factorial moments small, Fig. 3. No statistically significant rise is seen below an edge size of 0.4. The introduction of BE effects again gives something like a 0.05 increase in $<F_2>$ but, due to the generally lower level of $<F_2>$, the relative importance of including BE effects is much larger. Obviously, any trigger on the presence of jets in the events studied leads to much larger factorial moments, and also to an increase that continues down to much smaller regions in rapidity or azimuth. This is true already with a ordinary minijet trigger, i.e. $E_{Tjet} > 5$ GeV, Fig. 3.

The main conclusions of the Monte Carlo study on factorial moments thus are that

- a slicing in azimuth gives much lower values than a corresponding slicing in rapidity, mainly because local p_T compensation makes it less likely to find two particles nearby in angle;
- a simultaneous slicing in y and ϕ gives the largest variation as function of bin size, since one this way may pick up jet cores more cleanly;
- jet emission leads to intermittent behaviour, irrespectively of whether an initially emitted large-p_T parton is allowed to cascade into more partons or not; and
- Bose-Einstein effects are almost negligible for e^+e^- results, where the jet production mechanism dominates, but may be of more importance for minimum bias $p\bar{p}$ events, where the competition from other mechanisms for clustering is less severe.

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Table 1
Jet rate and other properties of jet and nojet events at 630 GeV, UA1 data[12,14] and different models. $<n_{ch}>$ and $<p_T>$ are evaluated for the region $|\eta| < 2.5$. Various uncertainties are involved in the attempted simulation of UA1 detector effects, so the detailed results (as opposed to the general trends) should be taken with a grain of salt.

	UA1	no multiple interactions	multiple interactions with matter distributed according to: simple Gaussian	double Gaussian
>1 jet fraction (%)	14.8	17.0	13.7	12.6
1 jet fraction (%)	9.96	14.30	10.79	8.88
2 jet fraction (%)	3.45	2.45	2.70	2.67
3 jet fraction (%)	1.12	0.22	0.19	0.74
4 jet fraction (%)	0.22	0.01	0.05	0.25
5 jet fraction (%)	0.05	0.00	0.01	0.07
$<n_{ch}>_{nojet}$	15.06	14.3	13.5	12.9
$<n_{ch}>_{jet}$	32.21	23.7	30.9	34.2
$<p_T>_{nojet}$ (GeV)	0.407	0.415	0.395	0.392
$<p_T>_{jet}$ (GeV)	0.502	0.508	0.473	0.471

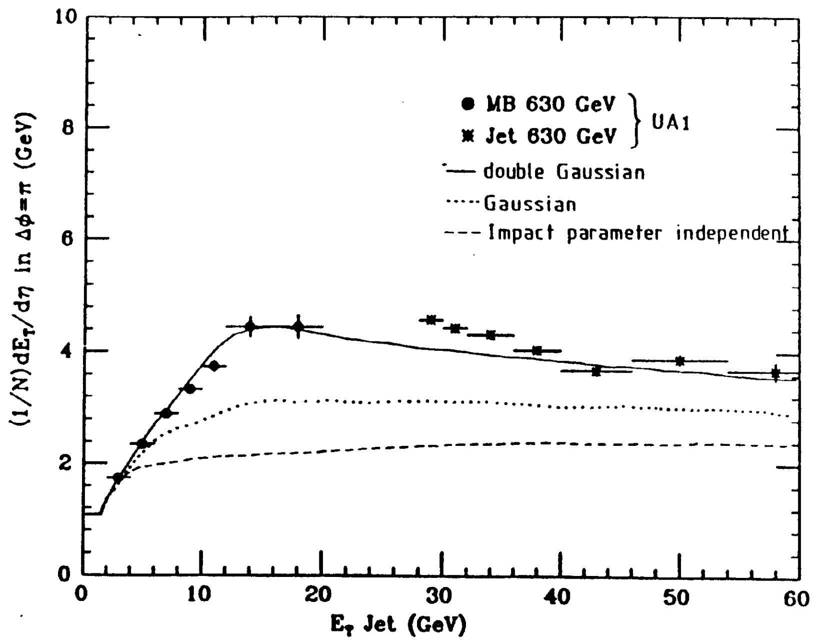

Figure 1
Average transverse energy $<dE_T/d\eta>$ in $1 \leq |\eta-\eta_{jet}| \leq 2$, $|\phi-\phi_{jet}| < 90^o$ as a function of the $E_{T jet}$ trigger. Data points UA1 at 630 GeV[14], dashed curve with impact parameter independent model, dotted with Gaussian and full with double Gaussian matter distribution.

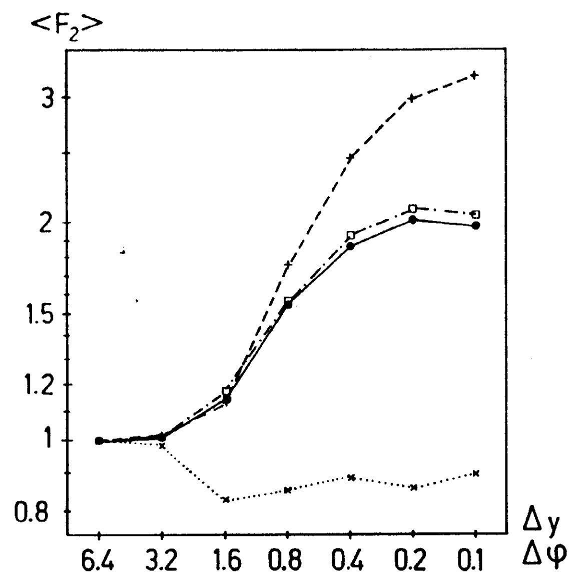

Figure 2
Second factorial moment for e^+e^- events at Z^0 peak in JETSET, as a function of bin size ($\Delta y \approx \Delta\phi$). Lines between the points only drawn to guide the eye. Dotted lines for two-jets only, dashed with second order matrix elements, full with parton shower and dash-dotted with parton shower plus Bose-Einstein effects. Statistical errors are not shown; they become larger for smaller bin sizes and are at most 10%.

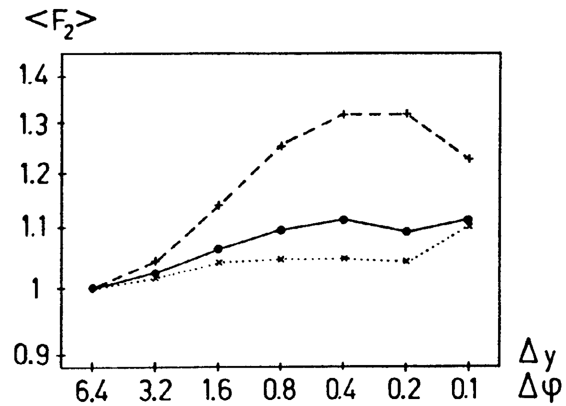

Figure 3
Second factorial moment for $p\bar{p}$ events at 630 GeV in PYTHIA. Dotted and full lines for minimum bias events without and with Bose-Einstein effects, dashed for minijet events with Bose-Einstein effects.